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Squelched Galaxies and Dark Halos

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ABSTRACT

There is accumulating evidence that the faint end of the galaxy luminosity function might be very different in different locations. The luminosity function might be rising in rich clusters and flat or declining in regions of low density. If galaxies form according to the model of hierarchical clustering then there should be many small halos compared to the number of big halos. If this theory is valid then there must be a mechanism that eliminates at least the visible component of galaxies in low density regions. A plausible mechanism is photoionization of the intergalactic medium at a time before the epoch that most dwarf galaxies form in low density regions but after the epoch of formation for similar systems that ultimately end up in rich clusters. The dynamical timescales are found to accommodate this hypothesis in a flat universe with $\Omega_m \lesssim 0.4$.

If small halos exist but simply cannot be located because they have never become the sites of significant star formation, they still might have dynamical manifestations. These manifestations are hard to identify in normal groups of galaxies because small halos do not make a significant contribution to the global mass budget. However, it could be entertained that there are clusters of halos where there are *only* small systems, clusters that are at the low mass end of the hierarchical tree. There may be places where only a few small galaxies managed to form, enough for us to identify and use as test probes of the potential. It turns out that such environments might be common. Four probable groups of dwarfs are identified within 5 Mpc and the assumption they are gravitationally bound suggests $M/L_B \sim 250 - 1000\ M_\odot/L_\odot$, $3 - 10$ times higher than typical values for groups with luminous galaxies.

Subject headings: cosmology: dark matter – galaxies: formation — galaxies: luminosity function, mass function

1. Expectations

According to the popular cold dark matter (CDM) hierarchical clustering model of galaxy formation there should be numerous low mass dark halos still around today. The approximation by Press & Schechter (1974) that initial density fluctuations would grow according to linear theory to a critical density and then collapse and virialize leads, with a CDM-like power spectrum, to a prediction of sharply increasing numbers of halos at smaller mass intervals. Cosmological simulations are now being realized with sufficient mass resolution to distinguish dwarf galaxies and this modeling basically confirms expectations of the existence of low mass halos (Klypin et al. 1999; Moore et al. 1999). Ninety percent of low mass halos accreted into a cluster may be disrupted by tidal stripping or absorbed by dynamical friction, but the halo mass function is still anticipated to steeply rise toward lower masses (Bullock, Kravtsov, & Weinberg 2000).

Indeed, dwarf galaxies are found in abundance in some environments. In the past, most observational effort has gone into studies in rich clusters because the statistical contrast is highest against the background (Smith, Driver, & Phillipps 1997; Trentham 1998; Phillipps et al. 1998; also the small but dense Fornax Cluster: Kambas et al. 2000). The general conclusion from these studies has been that, yes, there are substantial numbers of dwarfs of the spheroidal type. The high dwarf fraction reported in some instances may be in agreement with expectations of CDM hierarchical clustering theory.

However, there has been a suspicion that there might not be the expected abundance of dwarfs in environments less extreme in density than the rich clusters. Klypin et al. (1999) and Moore et al. (1999) have pointed out the apparent absence of large numbers of dwarfs in the Local Group. It is to be appreciated that the task of identifying extreme dwarfs is not trivial. They are tiny and faint. At substantial distances their surface brightnesses are faint against the sky foreground and close up they resolve into swarms of very faint stars. So dwarfs were not being found in the expected numbers but is this because of observational limitations?

Already at relatively high intrinsic luminosities there is good evidence of variations of the galaxy luminosity function with environment. The luminosity function is steeper (larger dwarf/giant fraction) in denser groups characterized by thermal X-ray emission or high velocity dispersions (Zabludoff & Mulchaey 2000; Christlein 2000). The trends are subtle in these studies because the faint end cutoffs barely include what would normally be considered dwarf galaxies. For example, Zabludoff & Mulchaey go comparatively faint, to $M_R = -16.6 + 5\log h_{75}$, where $h_{75} = \mathrm{H}_\circ/75$.

2. Ursa Major Cluster

Motivated by the speculation that the occurrence of dwarfs might be correlated with local density, we made extensive observations in the nearest environment where the density is low (dynamical time is long) yet where there are enough galaxies for a meaningful statistical discussion. We studied the Ursa Major Cluster, a structure fortuitously at about the same distance as the Virgo Cluster and which subtends a comparable amount of sky. The total light in bright galaxies in Ursa Major is about 1/4 that in Virgo but dynamical evidence suggests that the mass in Ursa Major is down by a factor 20 from that associated with Virgo (Tully & Shaya 1998). Roughly 16 sq. deg. of the Ursa Major Cluster were surveyed with deep CCD imaging with wide field cameras on the Canada-France-Hawaii Telescope and in the 21cm Hydrogen line with the Very Large Array. A projection of the survey on the sky is shown in Figure 1. Results of the two aspects of the survey are being reported respectively by Trentham, Tully, & Verheijen (2001) and Verheijen et al. (2000 and in preparation). Figure 2 conveys the important conclusion that the luminosity function is flat at the faint end in the Ursa Major Cluster. Whereas Phillipps et al. (1998) found ~ 700 galaxies per sq. deg. with $-16 < M_R < -11$ in Virgo, we find ~ 3 galaxies per sq. deg. in the same magnitude interval in Ursa Major. At the bright end, at $M_R < -17$, the number density of galaxies in Virgo is only 2.5 times higher than in Ursa Major so there is a relative difference of two orders of magnitude in counts at the faint end of the luminosity function between the two locations. The VLA survey confirms that there is no significant population of faint but HI rich systems in Ursa Major.

The Ursa Major luminosity function resembles the luminosity function of the Local Group and, indeed, of other nearby groups. The Ursa Major Cluster has a lot of galaxies but in other respects it resembles the nearby groups. It is a loose irregular cluster filled

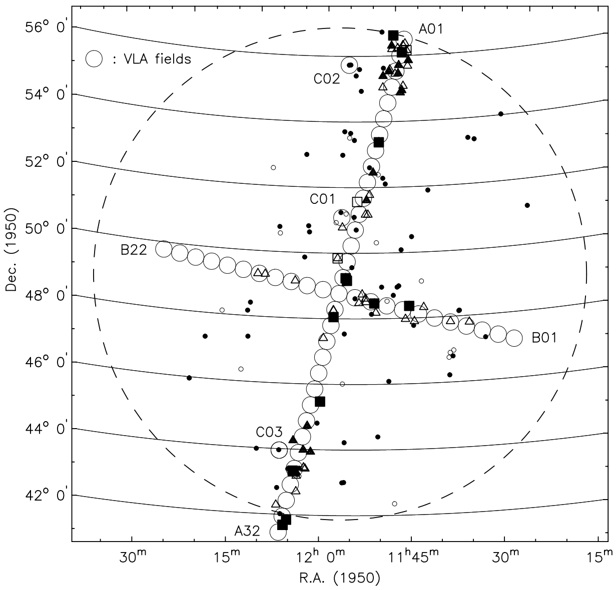

Fig. 1.— Ursa Major Cluster survey. The area covered by the VLA survey and with comparable fields by the CFHT wide field CCD survey is indicated by the pattern of circles. Before the survey began, the 79 galaxies indicated by small circles were known to be associated with the Ursa Major Cluster. The VLA HI survey detected only the 11 additional members within the survey footprint identified by filled squares. The CCD survey has revealed another 3 dozen probable or possible members indicated by filled and open triangles.

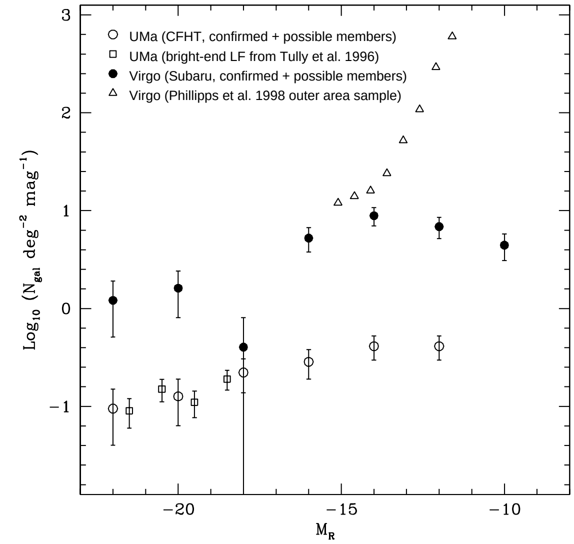

Fig. 2.— Comparison of luminosity functions. Open circles: luminosity function in the region of Ursa Major Cluster sampled by the CFHT wide field CCD survey. Open squares: complete bright end Ursa Major Cluster sample. Filled circles: luminosity function in the region of the Virgo Cluster sampled by the Subaru wide field CCD survey. Open triangles: Phillipps et al survey in Virgo Cluster.

with HI rich spirals with a crossing time comparable to a Hubble time. From the evidence at hand, such environments host relatively few faint dwarfs.

In contrast, the much more dynamically evolved Virgo and Fornax clusters appear to have much higher ratios of dwarf to giant galaxies (Phillipps et al. 1998; Kambas et al. 2000). Relative normalizations are an issue because selection criteria may differ and deep surveys cover only parts of the clusters. We are making observations with the wide field CCD cameras on Canada-France-Hawaii and Subaru telescopes, sampling nearby groups and clusters with a range of dynamical properties. At least our selection criteria are consistent. Results will be reported in later papers, but it is already apparent that the dwarf-to-giant ratio (with division between dwarf and giant at $M_R = -17 + 5\log h_{75}$) is *larger* in environments with short dynamical crossing times. This result is the inverse of the dark matter halo mass trends expected in a Cold Dark Matter hierarchical clustering model.

3. Squelched Galaxies

Hierarchical clustering theory anticipates that there should be numerous dwarf galaxies relative to giant galaxies and this situation is found in rich clusters. This theory predicts that the relative number of low mass sub-halos is even higher in low density regions (Sigad et al. 2000) yet fewer are actually seen. Apparently we need to explain the *absence* of small galaxies in low density environments. At first thought, it would seem that the rich clusters are more hostile, the low density regions more benign for the survival of small galaxies. In very low density groups dynamical collapse times can be of order the age of the universe so dynamical friction and tidal stripping have reduced consequences. Hence probably the explanation for the variance in dwarf/giant fraction does not lie with interactions between systems. We need to call upon a mechanism that *allows* small galaxies to form in rich clusters but *thwarts* small galaxy formation in places of low density.

A plausible mechanism is photoionization of the intergalactic medium before the epoch of galaxy formation. Efstathiou (1992) discussed the inhibiting effect on the formation of dwarfs due to the suppression of cooling of a primordial plasma of hydrogen and helium. Thoul & Weinberg (1996) took the discussion further with recourse to high resolution hydrodynamic simulations. These authors argue that gas heating before collapse is more important than inhibition of line cooling. The suppression of galaxy formation occurs below a virial velocity threshold. The UV background heats the precollapse gas to roughly 25,000 K. This temperature is much less than that associated with the virial energy of a large galaxy, hence has negligible effect on the collapse of baryons into a massive potential well. However, for a sufficiently small galaxy this heating is comparable with, or can dominate, the gravitational energy. Thoul & Weinberg and also Gnedin (2000) find there is essentially total suppression of baryon collapse for systems with circular velocities $V_{circ} \lesssim 30$ km s^{-1} and, by contrast, little effect on galaxy formation for systems with $V_{circ} \gtrsim 75$ km s^{-1}. It follows that luminosity functions would be little affected above $M_B \sim -18 + 5\log h_{75}$ but strongly attenuated below $M_B \sim -15 + 5\log h_{75}$.

The suppression of baryon collapse would only apply to galaxy formation that occurs after reheating of the intergalactic medium. The collapse timescale (Gunn & Gott 1972) is

$$t_{col} = 1.4 \times 10^{10} (R_{vir}^3/M_{14})^{1/2} h_{75}^{-1} \text{ yr} \qquad (1)$$

where R_{vir} is the virial radius in Mpc and M_{14} is the virial mass in units of $10^{14}\ M_\odot$. Values for R_{vir} and M_{14} can be extracted from Tully (1987) for the Virgo and Ursa Major clusters (R_{vir}: 0.79 and 0.98 Mpc respectively; M_{14}: 8.9 and 0.5 respectively). Hence, rough dynamical collapse times for these clusters are $t_{col}^{virgo} \sim 3.3$ Gyr and $t_{col}^{uma} \sim 19$ Gyr. The dense, elliptical dominated Virgo Cluster formed a *core* long ago and the loose, spiral dominated Ursa Major Cluster is still in the process of collapsing. Of course, galaxies continue to fall in and enlarge the Virgo Cluster to this day and, on the other hand, substructure in Ursa Major would have shorter dynamical collapse times than the entire entity.

Smaller mass scales collapse before larger mass scales. Dwarfs must form before their host cluster form. The timing of halo collapse and mergers as a function of environment will be considered in the next section. To conclude this section, we review the evidence on the timing of reionization of the intergalactic medium by the UV radiation of AGNs or hot stars.

Observations constrain the epoch of reionization to $z > 6$ (Fan et al. 2000), which can be understood on theoretical grounds (Gnedin & Ostriker 1997). In Figure 3 we see the relationship between redshift and the age of the universe for a wide range of topologically flat cosmological models. If baryon collapse into small galaxies can only occur before reionization then Fig. 3 tells us that if the epoch of reionization is as late as $z_{ion} \sim 6$ then dwarfs with $t_{col} \sim 1$ Gyr could form in a universe with matter density $\Omega_m \sim 0.2$ and vacuum energy density $\Omega_\Lambda \sim 0.8$.

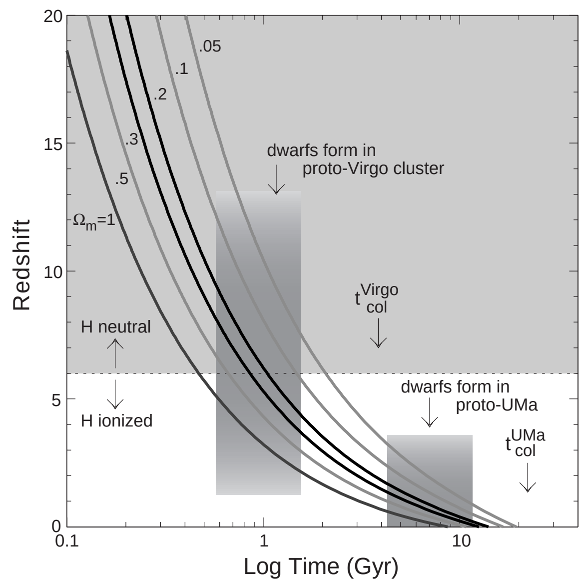

Fig. 3.— Redshift vs age of the universe for a range of flat world models, from $\Omega_m = 1$, $\Omega_\Lambda = 0$ on the bottom to $\Omega_m = 0.05$, $\Omega_\Lambda = 0.95$ on top. The arrows indicate the rough epochs of galaxy formation in the Virgo and Ursa Major clusters and the collapse timescales of the clusters. Intergalactic reionization must have occurred at $z_{ion} \gtrsim 6$; above, perhaps well above, the horizontal dotted line.

4. Simulations

We use semi-analytic models of galaxy formation based on the code developed by Somerville (1997) and described in detail by Somerville & Primack (1999) and Somerville, Primack, & Faber (2001). The formation history of collapsed dark matter halos and their sub-structure is described via Monte Carlo "merging trees" based on the extended Press-Schechter formalism (Somerville & Kolatt 1999). Radiative cooling by atomic Hydrogen, formation of stars, and feedback due to supernovae winds is modeled with simple empirical recipes, described in the references above. The effects of suppression of line cooling and photo-evaporation are neglected. In this paper, we also include a recipe to suppress gas accretion because of heating by an external photo-ionizing background, a feature not previously included in a full semi-analytic model. We describe this new ingredient briefly below. The concepts are discussed further by Somerville (2001).

A recipe for suppression of gas collapse is adopted from Gnedin (2000) and produces results consistent with Thoul & Weinberg (1996). Reionization is assumed to take place instantaneously at a redshift z_{ion}. In halos of virial mass M_{vir} that collapse before reionization, the mass of participating gas M_g available to ultimately make stars is:

$$M_g = f_b M_{vir} \tag{2}$$

where $f_b = \Omega_b/\Omega_m$ is the universal baryon fraction. In halos collapsing after reionization, there is suppression of the participation of gas in the collapse:

$$M_g = \frac{f_b M_{vir}}{[1 + 0.26 M_{50}/M_{vir}]^3} \tag{3}$$

where halos with M_{50} retain 50% of their baryon mass. Acceptable results are found if $M_{50}(z_c)$ is the mass associated with a halo with virial velocity 50 km s^{-1} at a collapse epoch z_c. Since halos collapsing later have lower density, $M_{50}(z_c)$ increases as z_c decreases. It follows from this recipe that, after reionization, gas collapse is suppressed completely in halos with $V_{cir} < 30$ km s^{-1} and is almost unaffected in halos with $V_{cir} > 75$ km s^{-1}. When this new ingredient is included, the luminosity function of satellite galaxies in the Local Group predicted by our model is in good agreement with observations (Somerville 2001).

When do dwarf galaxies form in environments of different total mass? This question can be addressed by following back the merger trees in semi-analytic simulations. As a matter of definition, it is taken that a sub-halo within a parent halo forms at the redshift z_f when the largest progenitor has a mass of half the final sub-halo mass. This discussion considers only final sub-halos with virial velocities in the range $17 < V_{cir} < 50$ km s^{-1}, the range strongly susceptible to squelching of star-formation by reionization.

The merger trees can be traced back in virialized parent halos with a range of masses, M_H. In Figure 4, we see the distribution of formation redshifts for squelchable dwarf halos embedded in parent halos with masses $10^{11} - 10^{14} M_\odot$. The solid histograms are based on the 'progenitor with half the final mass' definition of sub-halo formation while the dotted histograms represent the formation epoch of the 'oldest progenitor' (the redshift at which the first progenitor has gas at 10^4 K that can cool). The quantity dP/dz_f is the fraction of dwarf halos with formation redshifts in the interval z, $z + dz_f$.

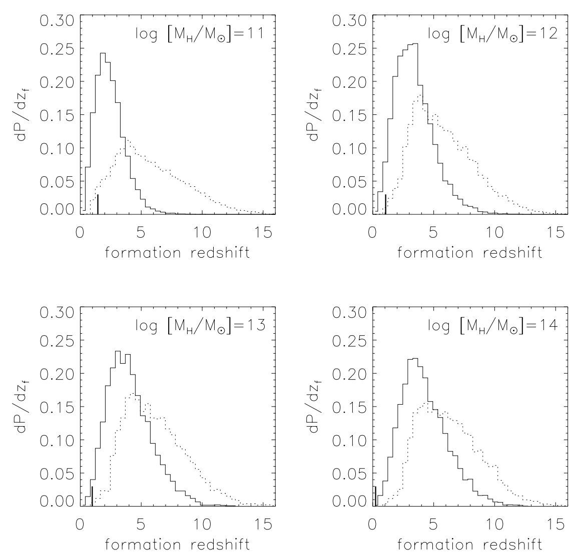

Fig. 4.— Distribution of formation redshifts for dwarf halos ($17 < V_{cir} < 50$ km s^{-1}) within virialized parent halos ranging from $10^{11} M_\odot$ to $10^{14} M_\odot$. Solid histograms: formation epoch defined by development of a progenitor with half the final dwarf sub-halo mass. Dotted histograms: formation epoch of first progenitor to cool. Dwarf galaxies tended to form earlier in environments that become more massive clusters.

The definition of the formation epoch in terms of the acquisition of a progenitor with 50% of the final mass is arbitrary. Figure 5 shows the cumulative distribution of the fraction of the final sub-halo mass that is in a single progenitor at $z = 8$; i.e. if we define $f \equiv M(z = 8)/M_0$ where M_0 is the final mass of the dwarf sub-halo, then the plot shows the fraction of objects whose largest progenitors have fractional mass greater than the quantity plotted on the x-axis. Thus, if we assume a simple picture in which a sub-halo survives squelching if it has some fraction of its final mass in place at reionization (as in the model of Bullock et al. 2001), then we can read the fraction of surviving galaxies off of the plot for any assumed value of the critical fraction f and for various parent halo masses. We see again that a much larger fraction of dwarfs will survive squelching in high-mass halos. The plot assumes $z_{ion} = 8$ but the results are insensitive to the precise epoch of reionization.

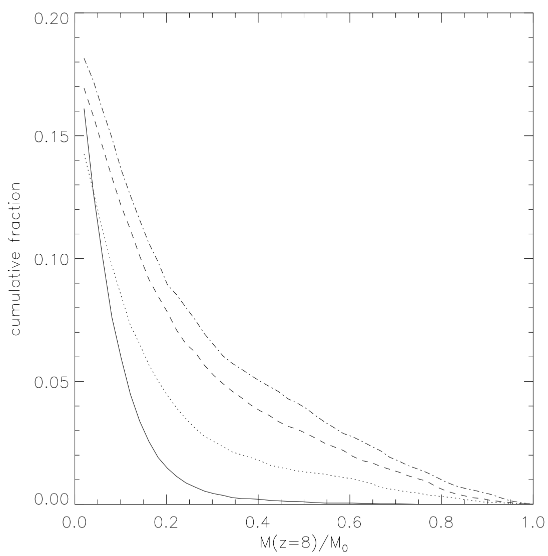

Fig. 5.— Cumulative fraction of sub-halos of ultimate mass M_0 in place by $z = 8$. The four curves differentiate between parent halos with a range of mass: $M_H = 10^{11} M_\odot$ (solid curve), $M_H = 10^{12} M_\odot$ (dotted curve), $M_H = 10^{13} M_\odot$ (dashed curve), and $M_H = 10^{14} M_\odot$ (dash-dot curve).

The quantity dP/dz_f shown in Fig. 4 can be integrated to determine the fraction of dwarf halos that formed before the epoch of reionization z_{ion} in any specified parent halo $P_{z_{ion}}(M_H, z_f > z_{ion})$. This quantity is the fraction of dwarf halos amenable to the collection of cold gas and hence the formation of a visible galaxy. Values for $P_{z_{ion}}$ are shown as a function of parent halo mass in Figure 6.

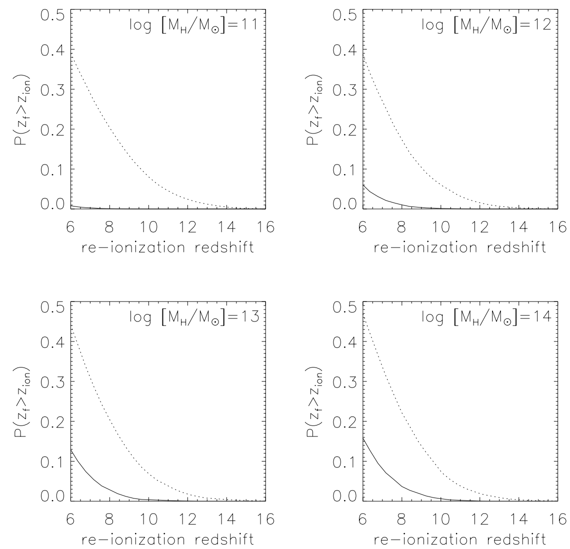

Fig. 6.— Fraction of dwarf halos accumulated before reionization in parent halos ranging in mass from $M_H = 10^{11} M_\odot$ to $M_H = 10^{14} M_\odot$. Solid curves: galaxy formation epoch defined by acquisition of half the final mass. Dotted curves: epoch of oldest progenitor.

Two clear conclusions can be drawn from this figure. First, whatever the epoch of reionization, the fraction of dwarf halos that can accumulate cold gas before reionization is greater in more massive parent halos. That is, dwarf halos formed earlier in environments that become massive clusters. Second, whatever the parent halo mass, the mechanism of star formation squelching by reionization is more effective the larger the redshift of reionization.

Qualitatively, it is plausible that the larger dwarf fraction in the Virgo Cluster ($8 \times 10^{14} M_\odot$) comes about because many dwarf halos were in place in the proto-Virgo region before reionization, while the smaller dwarf fraction in the Ursa Major Cluster ($4 \times 10^{13} M_\odot$; or smaller since U Ma is probably not virialized at this mass) is a consequence of the fact that few dwarf halos were in place before reionization. Interestingly, this squelching mechanism only produces a pronounced differential with environment in a universe with relatively low matter density, say $\Omega_m < 0.4$, $\Omega_\Lambda > 0.6$. In a universe with $\Omega_m = 1$, structure forms at low redshift: $t_{col} \sim 1$ Gyr corresponds to $z \sim 3$.

It would follow that if a range of cluster environments is explored then there should be a roll-over: denser clusters with short dynamical times will have a large dwarf/giant fraction and less dense clusters with long dynamical times will have a small dwarf/giant fraction. The collapse time scale associated with the break point density would reflect the time of reionization of the universe.

5. A Search for Dark Halos

If the preceding ideas have any merit then it follows that there would be many low mass halos that are not identified because they contain few stars or neutral gas. The cumulative amount of mass of such dark halos need not be significant compared with the cumulative mass of giant galaxy halos. Hence in groups or clusters containing giant galaxies the overall ratio of mass to light may be reflective of the properties of the dominant galaxies and their halos. However if groups could be identified that *only* have dwarf members then the contribution to the mass inventory from dark halos might be significant.

In a group catalog that includes galaxies of very low luminosities (Tully 1987, 1988) it already appeared that there may be bound systems of dwarf galaxies. With the passage of a decade there have been new dwarf identifications. In fact, the amount of new information is remarkably limited, evidence of an indirect nature that dwarf galaxies are not numerous. For our purposes, the most important new surveys for dwarfs are by Karachentseva & Karachentsev (1998) with follow up HI observations by Huchtmeier et al. (2000) and the study of the Sculptor and Centaurus regions by Coté et al. (1997).

Our new inventory of possible dwarf groups extends to $\sim$ 5 Mpc. Beyond this distance extreme dwarf galaxies tend to be too faint and deficient in HI to be reliably identified. The search is restricted to relatively high Galactic latitudes since dwarfs are very difficult to find in the Galactic plane. In this modest volume we find four groups of 3 or 4 dwarf galaxies each. One of these groups is, in fact, at the rather low latitude $b \sim 18$ in a region of low obscuration near the Galactic anti-center. The brightest galaxies in these groups have $M_B^{b,i} \sim -16$, with $V_{circ} \sim 45$ km s^{-1}. The global properties of these small groups are summarized in Table 1. The numeric names of the groups are drawn from Tully (1988).

Before focusing on the properties of these four small groups, it is worth a reflection on what else is going on within this 5 Mpc region. Beyond the Local Group there are four other groups at high galactic latitude with big galaxies: the Canes Venatici (14- 7), M81 (14-10), Sculptor (14-13), and Foreground Sculptor (14+13) groups (dominant galaxies: NGC 4736, NGC 3031, NGC 253, and NGC 55, respectively). Information is provided in Table 1 on these groups and also the group around M31 within the historical Local Group. The Centaurus (14-15) group flirts with the zone of obscuration at $b \sim 20$. There are three more groups at $|b| < 15$: Maffei–IC 342 (14-11), Circinus (14+20), and a newly revealed group around NGC 6946. Otherwise there are precious few galaxies known in the local region; a couple of pairs and a dozen other galaxies with $M_R < -15$ not associated with groups but within the filaments called 14 and 17 (Tully 1988). We should have a complete census of all HI-rich systems at $|b| \gtrsim 20$, $M_B < -14$, and $d < 5$ Mpc. Hence the four dwarf groups identified in Table 1 are clearly distinguished. The number of high latitude dwarf groups is comparable to the number of high latitude groups with giant galaxies, though the number of members per group are fewer. Given the small dimensions and velocity dispersions, the dwarf groups represent a manifest correlation enhancement over an unclustered distribution.

The dimension, velocity dispersion, light, and inferred mass properties of the dwarf groups can be compared with the properties of more familiar groups containing large galaxies (Tully 1987). In the summary provided in Table 1, projected radii $< R_p >$ are the mean projected separations from the geometric centers of the identified members with no weighting. $< R_{3d} >$ are the equivalent 3-dimensional radii, directly measured in the cases of the groups including NGC 3109 and NGC 224 (M31), but only derived statistically from $(\pi/2) < R_p >$ for the cases in brackets. Velocity dispersions σ_V are rms differences in radial motions from the group mean with no weighting. Masses are calculated based on the 'projected mass estimator' of Heisler, Tremaine, & Bahcall (1985)

$$M = \frac{f_{pm}}{G(N-\alpha)} \sum_i^N R_{p,i} \Delta V_i^2 \qquad (4)$$

where $f_{pm} = 20/\pi$ is found by Tully (1987) to be statistically compatible with masses derived using the virial theorem (becomes $f_{pm}^{3d} = 5$ and R_p becomes R_{3d} in the cases of the NGC 3109 and NGC 224 groups where three-dimensional positions are available), N is the number of group members, and $\alpha = 1.5$ following Heisler et al. The projected mass estimator and R_p are more stable than the virial mass estimator and virial or harmonic radius in cases where there are close projections. We make the underlying assumption that the galaxies are only test particles in the gravitational potential well so luminosity weighting is inappropriate and there may not be any galaxy at the actual minimum of the potential. The groups are expected to be bound but not virialized so mass estimates in these non-equilibrium conditions are uncertain.

The group including NGC 3109 is the nearest neighboring group to the Local Group. It is so near that it has sometimes been considered as part of the Local Group but galactocentric velocities are all positive and the dispersion in velocities is tiny. Good distances, accurate to $\sim 10\%$, are available for all the prospective members from observations of either Cepheids or the luminosities of stars at the tip of the red giant branch. The remarkably similar distances place these galaxies together and substantially beyond the Local Group (van den Bergh 1999). The group has dimensions similar to groups with luminous galaxies (Tully 1987) and the extreme number density contrast over an average volume of space makes it likely these galaxies are mutually bound.

Distances to the other dwarf groups are considerably less certain. Nevertheless, the basic results seem well established. Group dimensions are similar to those of more familiar spiral groups. Velocity dispersions are very low, hence inferred masses are low. However since these are low luminosity groups, M/L_B ratios are large. By comparison, more prominent groups have $M/L_B = 94\ M_\odot/L_\odot \pm$ factor 2 (Tully 1987; same distance and luminosity scales). The statistics are still slim but the groups of dwarf galaxies seem to have M/L_B values 4 or 5 times higher. It would follow from our working hypothesis that $75 - 80\%$ of the original baryon content has not become stars.

The group luminosities and estimated masses are plotted in Figure 7. Groups within 5 Mpc are indicated by the big symbols and constitute a reasonably complete, though skimpy sample. The triangle distinguishes the M31 group as identified by Evans et al. (2000). The dwarf groups identified in this paper are distinguished by low estimated masses and *very low* luminosities. Small symbols characterize luminous groups with $5 < d < 10$ Mpc, where d is distance.

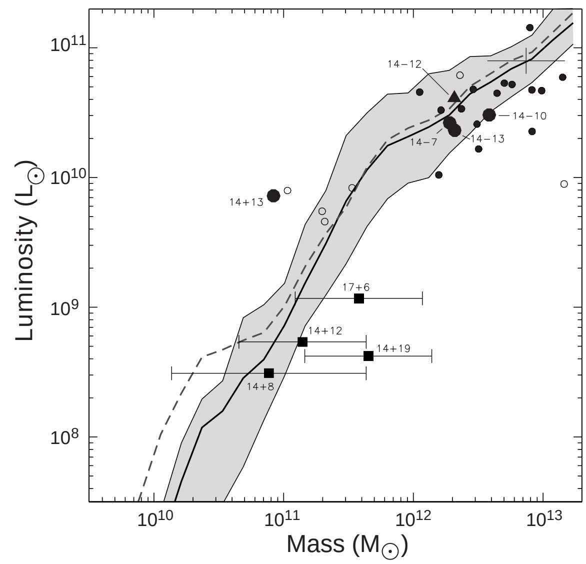

Fig. 7.— Group mass vs. B-band group luminosity. Filled circles: groups with 5 or more known members identified on a basis of luminosity density (Tully 1987). Open circles: such groups of 3 or 4. Filled squares: dwarf groups identified in this paper. Large symbols: groups within 5 Mpc and at high galactic latitude. Small symbols: other known groups within 10 Mpc. Filled triangle: the low latitude but well defined M31 group. The mean mass and luminosity values for the sample of 49 nearby groups with 5 or more members discused by Tully is indicated by the cross in the upper right corner. The horizontal arm of this cross indicates the factor 2 rms scatter in mass at a given luminosity found in the sample of 49 groups. The solid bold line show the mean results from semi-analytic models with the recipe for 'squelching' as described in the text. The grey domain includes 90% of the model results. The dashed line shows the mean results for models without squelching.

The group 14+13, including NGC 55 and NGC 300, lies in an interesting intermediate location in Fig. 7. This second nearest group is well defined by a swarm of dwarfs (Coté et al. 1997). The virial mass is very low (velocity dispersion of 10 galaxies only 18 km s^{-1}), in the range of the groups of dwarfs. However, the 14+13, or 'Foreground Sculptor' group has two intermediate-sized galaxies so no deficiency of light.

The curves superimposed on Fig. 7 are derived from the semi-analytic modeling with and without the photoionization squelching. The modeling incorporates the currently favored ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h_{75} = 1$, $\sigma_8 = 1$, and $\Omega_b = 0.032\ h_{75}^{-2}$. The merging history of each halo is traced down to a limiting resolution of $V_{cir} = 16$ km s^{-1}, corresponding to a virial temperature of about 10^4 K. Below this temperature, gas cannot cool via atomic processes. In Fig. 7, curves show the mean total luminosities from the modeling as a function of halo mass, for two cases: with no squelching (dashed line) and with squelching due to reionization at $z_{ion} = 10$ (solid line). The results of squelched models are similar for $z_{ion} = 6 - 100$. Without squelching, the ratio of light to mass is only a weak function of mass above $M_{vir} \sim 10^{10} M_\odot$, rising slightly higher at intermediate masses. The turndown below $M_{vir} \sim 10^{10} M_\odot$ is mainly due to supernova feedback. Below $M_{vir} \sim 10^9 M_\odot$ there is a further cutoff because gas is not cooled by atomic processes. Squelching introduces a strong cutoff at masses below about $10^{11} M_\odot$. In detail, there is a systematic that causes a displacement of the solid curve in Fig. 7. The modeling pertains to virialized halos but the dwarf groups are most unlikely to be virialized. The process of clustering in the dwarf groups is less far along than would be the case with virialized groups of the same mass. One can suppose that the dwarf groups might be composed of virialized sub-halos with masses of $1 - 3 \times 10^{10} M_\odot$ and scales of 45-60 kpc which are in the extended process of merging. Suppression by reionization is greater at these very low sub-halo masses than at the bound group mass scale.

6. Summary

1. The faint end of the luminosity function of galaxies might be rising in the dense environment of rich clusters but flat or falling in the low density regions of groups. Cold Dark Matter theory predicts that the dark matter halo mass function is sharply rising at the low mass end. It seems something is suppressing the visible manifestations of small galaxies in low density environments.

2. Reionization of the universe at $z_{ion} > 6$ could inhibit the collapse of gas in low mass potential wells for late forming galaxies. Dynamical collapse times inferred from the observed densities of clusters are consistent with the picture that relatively more dwarf halos formed *before* reionization in high density regions and relatively more formed *after* reionization in low density regions, but only if structure is forming at high redshift; ie, $\Omega_m \lesssim 0.4$ in a flat universe.

3. Using semi-analytic models with a recipe for suppression of gas collapse into low mass halos after reionization, within a ΛCDM cosmology, it is shown that more dwarf halos formed earlier in regions that ultimately become massive clusters. This statement refers to dwarf halos that avoid disruption or absorption and survive until today; many more halos formed early and are now lost. Qualitatively, the models anticipate that more dwarf halos were in place before reionization in proto-cluster environments and, compared with moderate density regions, the ratio of dwarf to giant galaxies should be larger. This fundamental expectation appears to be observed.

4. Four small groups that only contain dwarf galaxies are found within 5 Mpc, comparable to the number of groups that contain large galaxies. Dynamical evidence is found for a lot of dark matter in these groups, with $M/L_B \sim 250 - 1000\ M_\odot/L_\odot$, 3-10 times higher than in groups with big galaxies. It is suggested that low mass halos which never hosted significant star formation make up a significant fraction of the group mass in these places.

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Table 1. Properties of groups within 5 Mpc

Group	Brightest galaxy	No.	Dist. Mpc	$< R_p >$ kpc	$< R_{3d} >$ kpc	σ_V km s^{-1}	M 10^{11} $M_\odot$	L_B 10^8 $L_\odot$	M/L_B $M_\odot/L_\odot$
14− 7	NGC 4736	22	4.8	538	(845)	53	19.4	264.	72
14−10	NGC 3031	12	3.1	322	(506)	107	38.5	304.	127
14−13	NGC 253	7	3.0	495	(778)	69	20.8	231.	90
14+13	NGC 55	10	1.8	298	(468)	18	0.84	72.	12
14−12	NGC 224	16	0.8	178	188	77	20.7	409.	50
14+12	NGC 3109	4	1.4	330	335	18	1.4	5.4	270
14+ 8	UGC 8760	3	5	180	(283)	16	0.77	3.1	250
14+19	UGC 3974	4	5	356	(560)	28	4.5	4.2	1060
17+ 6	NGC 784	4	4	128	(201)	36	3.8	11.7	330

Notes to Table 1. Group memberships.

Groups $|b| > 30$ with luminous galaxies

Group 14−7: CVn I group – NGC 4736, NGC 4449, NGC 4244, NGC 4214, NGC 4395, many smaller galaxies

Group 14−10: M81 group – NGC 3031, NGC 2403, NGC 3034, NGC 3077, NGC 2366, NGC 2976, 6 others

Group 14−13: Sculptor group – NGC 253, NGC 247, NGC 7793, 4 dwarfs

Group 14+13: Foreground Sculptor – NGC 55, NGC 300, 8 dwarfs

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Low latitude special case

Group 14−12: M31 group – NGC 224, NGC 598, IC 10, NGC 205, NGC 221, 11 dwarfs

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Groups with only dwarfs

Group 14+12: NGC 3109 (1.36 Mpc), Sextans A (1.45 Mpc), Sextans B (1.34 Mpc), Antlia dwarf (1.33 Mpc)

Group 14+ 8: UGC 8651, UGC 8760, UGC 8833

Group 14+19: UGC 3755, UGC 3974, UGC 4115, KK98 65

Group 17+ 6: NGC 784, UGC 1281, KK98 16, KK98 17

KK98 objects are from survey by Karachentseva & Karachentsev (1998)